

CHROMATIC PHENOMENA PRODUCED BY INTER- MITTENT STIMULATION OF THE RETINA

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INTRODUCTION

The classical formulations of the relationship between experience and stimulation have largely neglected the dimension of time. In other words, to borrow some terms from physics, these formulations have concerned themselves principally with what might be called the 'steady state' phenomena. But the 'transient' phenomena, of which, in vision, the Fechner-Benham colors are an example, present a problem of certainly greater difficulty and theoretical importance. Neglect of the 'transient' phenomena encourages theorizing in terms of functional 'atoms' of the form: stimulus—excitation—sensation. With the blessing of the Doctrine of Specific Energies, the inevitable result is a body and soul (receptor, central projection and 'sensation') theory, logically no better than the body and soul theories of the most ancient tradition.

The experiments herein reported constitute an attempt to penetrate a little further into the mysteries of those visual 'transients' known as the Fechner-Benham colors and certain other apparently closely related phenomena.

Originally discovered by Fechner (8), the phenomenon was popularized by Benham (3), who devised the now usual method of producing the colors. This consists of a disc which is half black and half white, on the white part of which are segments of concentric black rings (Fig. 1A). When rotated clockwise the inner rings appear reddish and the outer rings bluish. Reversing the direction of the rotation reverses the coloration of the rings.

The colors observed in the rings are apparently dependent upon the speed of rotation, the lengths and widths of the concentric rings and other physical variation in the stimulus pattern (2, 16, 17).

Related to the Fechner-Benham phenomena are the colors producible in stationary stimulus patterns, involving, as with the discs, adjacent black and white areas. The Luckiesh-Moss line pattern (15)—Fig. 1B—and the Skinner disc pattern (20)—Fig. 1C—give

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rise to a series of complex perceptions of color and movement when steadily fixated.

The interpretations of the Fechner-Benham phenomena due to rotating discs are of two types. The general form of the first postulates different latencies of several photochemical processes of the



FIG. 1A. Benham disc

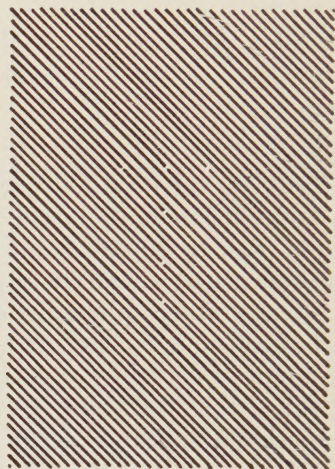


FIG. 1B. Luckiesh-Moss line pattern

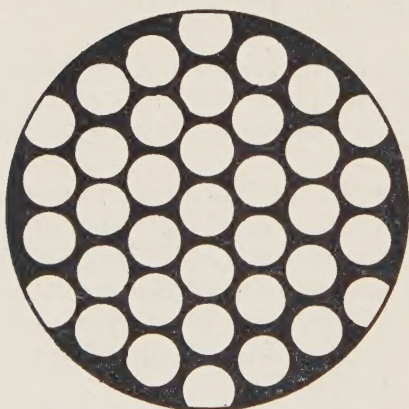


FIG. 1C. Skinner disc pattern

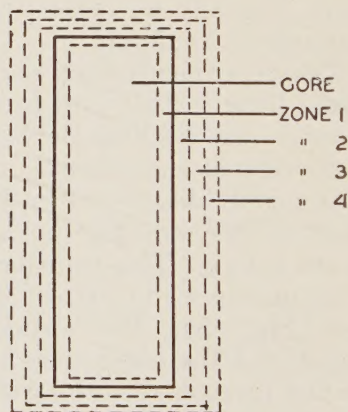


FIG. 1D. Zoning effect

receptor mechanism. These processes, when stimulated, do not begin and cease to respond at the same speeds: their excitation curves reach their maxima and minima at different rates. Thus the different degrees of participation of these chromatic components in the total effect will depend upon the temporal and spatial aspects of the stimulus pattern (3, 8, 9, 17).¹

¹ For detailed summaries see Bagley (2), Piéron (17) and Erb and Dallenbach (7).

The second type of theoretical approach is based by Fry (10) on the modulation theory of Troland (22). Fry attempts to show that the Fechner-Benham phenomenon depends on the principle of a "complicated stimulus pattern which involves the stimulation of adjacent areas of the retina with different temporal patterns of intermittent white light." He holds that the Fechner colors are compatible with Troland's theory on the basis that intermittence alone² will produce colors and that the classical Benham disc provides merely a special pattern of intermittence.

As yet only a few suggestions have been made to explain the color perceptions from the stationary patterns. Erb and Dallenbach (7) investigated the bearing of eye movements on the colors and concluded that "the 'subjective' colors are to some extent dependent upon eye movement, but eye movement, though necessary, does not appear to be a sufficient or compulsory condition." They also state that the colors are enhanced when fixation is not in the plane of the figure.³ Skinner (20) suggests an explanation for the colors seen on his disc pattern which hypothesizes a disproportionate activity in the cone processes and hence the same effect as that of stimulation by colored light.

Both the revolving discs and the stationary patterns have been observed under chromatic as well as neutral illumination. The few studies available, however, have contributed little to the general theory (1, 17, 18).

APPARATUS

The results of previous investigations suggest that an indispensable physical condition necessary for the production of the Fechner colors is some form of intermittent or variable stimulation of the retina. They also suggest that the phase relation between the intermittent stimulations of adjoining regions of the retina is an important modifying factor. The Benham top and the stationary pattern both fulfill this condition, the one by alternate dark and light flashes produced by the black and white sectors and the other by some complex of eye movements which causes oscillatory shifting of the stimulus pattern on the retina. However, a much wider latitude for experimental variation of conditions is gained by an arrangement which provides independently variable illuminations of figure and ground in a stationary pattern, in contrast with the Benham disc, where the ratio of the luminosities of the bright and dark regions is fixed, no matter what the absolute level of the illumination may be. If it is possible in the case of these fields to vary (1) the luminosities independently, (2) the frequencies of intermittence over a continuous range up to the critical flicker frequency, (3) the on and off ratios independently, and (4) the phase relationships, all variations in the physical conditions involved in the production of the phenomena in question can be arranged. To this end the apparatus described in detail elsewhere in this Journal was adapted (4). Here will be given only a brief sketch of the stimulus arrangement serving the left eye, the eye used in all experiments to be discussed.

The left ocular, L_f (Fig. 2), consists of an arrangement of flashed opal diffusing surfaces, f , F_1 and F_2 . These are independently illuminated by 240-watt, d.c., GE airplane headlight lamps (L_1 , L_2 and L_3) which, when mounted with a set of appropriate lenses, provide a powerful light source. The flashed opal surfaces are visible to the eye of the observer at X by virtue of

² See Purkinje, J. E. (19), Ch. I, Vol. I.

³ Further evidence of this implied blurring factor is offered later in the present paper.

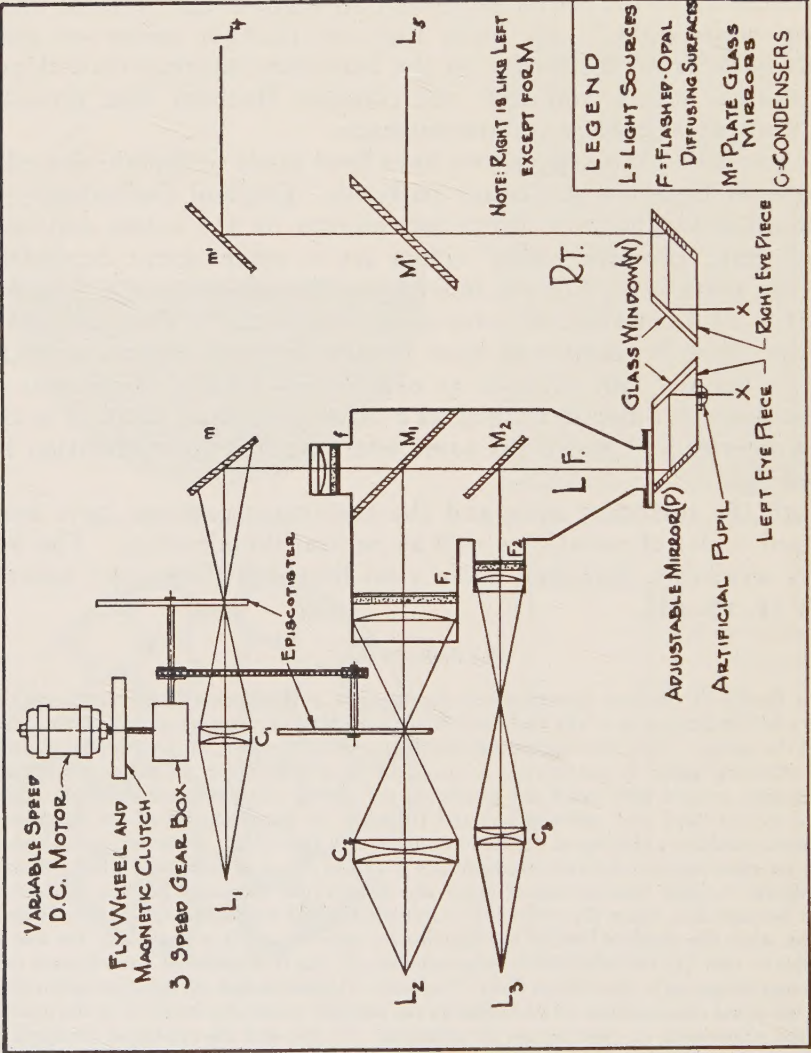


Fig. 2. Apparatus for presentation of stimulus

the mirrors m , M_1 and M_2 , which are placed at 45° angles with respect to the optical axis of the system. An area of silver of any size or shape may be scraped from the backs of M_1 and M_2 and thus three fields are provided: F_1 and F_2 , whose images are seen in M_1 and M_2 , and f , which is seen directly through M_1 and M_2 . Any combination of these three fields may be arranged by removing certain of the mirrors, by using partially silvered mirrors, or by using mirrors which have been desilvered over certain areas.

The mirrors M_1 and M_2 are mounted in a large cylindrical tube in which is sealed a mineral oil whose refractive index (1.481) is approximately that of the glass in the mirrors (1.517). By making the system optically homogeneous any reflex images occasioned by differences in refractive indices are eliminated. The oil is held in the tubes by glass retaining windows and the surfaces f , F_1 and F_2 are placed in optical contact with them by a film of oil.

In the eye-piece attached to the tube an adjustable mirror (E) for centering the field is located. This sends the light to a glass window which with total reflection passes the light into the eye of the observer. The external orifice of the eye-piece may be fitted with artificial pupils of any desired aperture.

The optical system just described produced a maximal field brightness of 501 millilamberts as determined by standard photometric means. Neutral filters of the proper density were used to produce lower field brightnesses.

When set up for the actual experiments only m and M_1 were used. The silver was removed from a small circular area on the back of M_1 so that light from m could be seen through M_1 . The small circular spot, elliptical as seen through the eye-piece, since M_1 sets at a 45° angle to the optical axis of the tube, thus constituted a figure seen against the ground provided by M_1 . Two episcotisters were placed in the paths of L_1 and L_2 to cut the light at the point of focus. This expedient achieved the sharpest cutoff. The episcotister discs consisted of two open and two closed 90° sectors which could be shifted with respect to each other to change the phase relationships between the on and off periods of the figure and the ground. The episcotisters were coupled by a chain and sprocket system to maintain synchronism and were driven by a large, variable speed, d.c. motor equipped with a 28-pound fly wheel to eliminate short period fluctuations. Speed of rotation of the episcotisters was governed by a three-speed gear box and a set of resistances in series with the motor. The number of flashes per sec (F.P.S.) could be continuously varied from one flash per sec. to 60.

Three kinds of illumination were used: almost white, unfiltered light; red; green.

To obtain red light suitable for this investigation it was necessary to be certain that the filter used would transmit no radiation of wave length shorter than $650\text{ m}\mu$. Wave lengths longer than $650\text{ m}\mu$ probably stimulate the postulated G retinal process negligibly, if at all, and hence should involve the R process only. The Wratten No. 89 red filter fulfills this condition. Photometric calibration of the particular filter used gave its transmission factor as .0025. This filter provided a field brightness at M_1 of 1.25 millilamberts.

A green filter which transmits a narrow band of light is difficult to find, and from a physiological standpoint no green illuminant, however monochromatic, stimulates the G retinal process only: the R and B processes will be affected. However, a green filter constructed in accordance with Gibson's specification was employed. Gibson (15) used a combination of glasses which transmits light at $560\text{ m}\mu$:

- (a) Corning: 351, 4.55 mm. in thickness.
- (b) Corning: didymium, 5.82 mm. in thickness.
- (c) Jena: VG - 3, 1.99 mm. in thickness.
- (d) Jena: BG - 18, 1.94 mm. in thickness.

This combination has, according to Gibson, a spectral centroid of $560\text{ m}\mu$ for any daylight or incandescent illuminant. The transmission factor of the green filter was .0237, which yielded a brightness at M_1 of 11.8 millilamberts.

In the experiments to be described the conditions of observation were the same. The position of the S's head was determined by an adjustable head rest and a tooth bit so that the left eye always occupied the same position with respect to the eye-piece. The eye-piece was enclosed with a black cloth, the ends of which S arranged about his eye so that no light except that from the eye-piece could enter the left eye, and no light at all, the right.

The three Ss used were observers of considerable experience. Two had spent many hours in observing such visual effects. The third was less practiced, although he had had some previous experience in the process of observing and describing the Fechner colors.

Observer A.—(The least practiced.) Male. Age 26. Myopic, slight astigmatism. Wears glasses. Left eye correction: -2.25 . Normal trichromat.

Observer B.—Male. Age 28. Myopic, slight astigmatism. Wears glasses. Left eye correction: -2.50 . Normal trichromat.

Observer C.—Male. Age 48. Myopic, pronounced astigmatism. Presbyopic. Wears glasses. Left eye correction: -2.25 . Normal trichromat.

After adaptation to the brightness level of the instrument the Ss described what they saw at the position of the figure and on the surrounding field. The colors were reported in accordance with instruction in the color naming system which makes red-orange (RO), for example, a color which lies spectrally between the reds and the oranges and contains more orange than red. The series of notations used by S and recorded by E was: R—OR—RO—O—YO—OY—Y—GY—YG—G—BG—GB—B—VB—BV—V. The symbol for purple was P; for white, W; for black, B; for gray, A (achromatic); for Brown, Br. In cases where complex phenomena were observed, E made labeled diagrams representing the pattern of the effects described by the Ss. These were checked by S.

PROCEDURE AND RESULTS

Part I

Preliminary Observations with White, Red and Green Light.—With M_1 , a mirror with a circular hole .189 in. in diameter, an extensive series of episcotister speeds and phase settings were tested. Under all conditions the figure and the ground were equal in brightness and their illuminations were qualitatively alike.

Schedule of speeds and settings used in Part I:

1. Frequencies of 2, 4, 6, 10, 15 and 20 F.P.S.
2. Phase lead of ground over figure: 18° , 36° , 54° , 72° and 90° .
3. Phase lead of figure over ground: 18° , 36° , 54° and 72° .

Subjects A and B.

With white light of maximal field brightness (501 millilamberts) good colors were observed on the figure under nearly all conditions (Table I). These were mostly desaturated yellows and greenish yellows, although a few greens, greenish blues and violets were noted. Changes in flash frequency and phase relationship had no consistent effect on colors observed, nor did the Ss agree well on what they experienced under the same conditions. A condition of decreased illumination (7 millilamberts) yielded about the same results, except that the predominant yellows at the high illumination gave way to greens (Table II).

Since the transmission factor of the red filter used was low (field brightness 1.25 millilamberts), studies were made on white light of very low intensity for purposes of comparison. Two neutral filters of low transmission were used to obtain field brightnesses of 1.3 and .55 millilamberts. Under these conditions colors were reported by Subject B, but not by Subject A (Table III). They were principally variations of red with a few weak violets appearing at certain settings.

TABLE I

COLORS OBSERVED WITH WHITE LIGHT AT VARIOUS FLASH FREQUENCIES AND PHASE SETTINGS WITH ELLIPTICAL FIGURES

Figure and ground brightness: 501 millilamberts

F.P.S.	Subject	Lead of ground over figure in degrees:				
		18°	36°	54°	72°	90°
2	A	Y	GY	Y	Y	Y
	B	?	O	G	?	Y
4	A	Y	Y	G	G	Y
	B	Y	Y	YG	OY	G
6	A	Y	Y	Y	GY	G
	B	Y	Y	Y	OY	G
10	A	Y	Y	Y	Y	Y
	B	OY	OY	Y	Y	?
15	A	OY	OY	O	OY	OY
	B	OR	O	O	YO	R
20	A	Y	Y	YO	OY	YO?
	B	YO	OY	OY	OR	R
Lead of figure over ground in degrees:						
F.P.S.	Subject	18°	36°	54°	72°	90°
2	A	—	—	Y?	Y?	Y
	B	V	V	?	?	Y?
4	A	Y	Y	YG	Y	Y
	B	V	B	?	Y	YG
6	A	V	?	YG	GB	G
	B	V	V or B	B	Y	G
10	A	—	—	YG	Y	Y
	B	V	GB	YG	YO	?
15	A	—	—	YO	OY	OY
	B	V?	G	Y	OR	R
20	A	—	—	YO	Y	YO
	B	?	V	YO	O	R

Note: At the lower flash frequencies both the light and dark phases of the cycles were seen on the spot. Usually it was the light interval which was colored, the dark interval being achromatic.

Red light and green light tested under the phase and flash frequency settings described above yielded no colors other than red, in the case of the red light, and green, in the case of the green light, for Subjects A and B. When the above findings were checked by Subject C, however, extremely complicated color patterns were reported.

The observations of C differed from those of A and B in two fundamental respects:

a. C was able to see colors when approximately monochromatic illuminations were used, and

b. C was able to see, under all conditions of illumination, complex patterns of colors on and around the figure instead of a more or less homogeneously colored spot.

TABLE II

COLORS OBSERVED WITH WHITE LIGHT AT VARIOUS FLASH FREQUENCIES AND PHASE SETTINGS WITH ELLIPTICAL FIGURES

Figure and ground brightness: 7 millilamberts

F.P.S.	Subject	Lead of ground over figure in degrees:				
		18°	36°	54°	72°	90°
2	A	A	A	A	A	A
	B	A	A	G?	G?	A
4	A	BG	GB	A	A	A
	B	G	O	A	YG	YG
6	A	Y	Y	Y	Y	A
	B	G	G	G	G	YG
10	A	GB	GB	GB	G	GY
	B	G	G	G	G	G
15	A	—	—	A	A	Y?
	B	GY	G	G	G	G
20	A	—	—	—	A	A
	B	A	G	G	G?	G
		Lead of figure over ground in degrees:				
F.P.S.	Subject	18°	36°	54°	72°	90°
2	A	Y	Y	Y	Y	A
	B	Y	Y	Y	YG	YG
4	A	Y	Y	Y	Y	A
	B	Y	Y	YO	YG	YG
6	A	Y	Y	Y	Y	A
	B	Y	Y	Y	YG	YG
10	A	Y	YG	YG	YG	GY
	B	A	A	G	G	G
15	A	—	Y	A	Y?	Y
	B	A?	GB?	G	G	G
20	A	—	—	—	A	A
	B	A	GB	G	G	G

TABLE III

COLORS OBSERVED AT VARIOUS FLASH FREQUENCIES AND PHASE SETTINGS
WITH WHITE LIGHT AND ELLIPTICAL FIGURES

Figure and ground brightness: 1.3 millilamberts

F.P.S.	Lead of ground over figure in degrees:				
	18°	36°	54°	72°	90°
2	A	A	A	A	A
4	A	R?	R?	?	A
6	—	R?	R	R	R
10	—	R	B?	P?	P?
15	—	—	—	—	V?
20	—	—	—	—	—

F.P.S.	Lead of figure over ground in degrees:				
	18°	36°	54°	72°	90°
2	A	A	A	A	A
4	A	O	O	R	A
6	P?	R	R?	R	R
10	V	V	V	V	R?B?
15	—	—	—	—	V?
20	—	—	—	—	—

Figure and ground brightness: .55 millilamberts

F.P.S.	Lead of ground over figure in degrees:				
	18°	36°	54°	72°	90°
2	A	A	A	A	A
4	A	A	R?	R	R?
6	A	A	A	R?	R?
10	A	A	A	B?	A
15	—	—	—	—	—
20	—	—	—	—	—

F.P.S.	Lead of figure over ground in degrees:				
	18°	36°	54°	72°	90°
2	A	A	A	A	A
4	A	R?	R	R	R?
6	A	P?	R?	R?	R?
10	A	A	A	A	A
15	—	—	—	—	—
20	—	—	—	—	—

The contradictory data are not clearly to be accounted for by ocular differences between C and A and B, although it was these differences that suggested the following investigations. Possibly C's greater astigmatism, impaired accommodation and slight lens cloudiness might contribute to produce a somewhat diffuse illumination of

the retina. It is well known that blurring the boundary enhances simultaneous contrast and it was thought that reducing the sharpness of the boundary between figure and ground might similarly affect the perceptions.

Part II

Reduction of Boundary Sharpness.—A means for producing some blurring of the boundary of the figure was provided by placing small glass discs finely etched with levitated alumina in the eye-piece. The glass discs produce a 74 percent transmission loss. Comparable brightnesses without the blurring effects were obtained with appropriate filters.

Under these conditons both A and B reported colors when red and green illumination was used. They also reported the presence of colored borders with white light. Some degree of indistinctness at the boundary of figure and ground enhanced and complicated the chromatic phenomena observed with white light and produced colors under conditions of monochromatic illumination where they were absent before.

The border phenomena experienced with the elliptical figure were extremely difficult to hold long enough to observe and describe. The most assiduously maintained fixation proved to be insufficiently rigid to allow for careful observation. It was then thought that a long, straight boundary might afford more stable border effects than the small, curved boundary of ellipse. To this end, bars were formed by scraping the silver from the backs of the mirrors, just as in the case of the other figures. The bars were all $\frac{3}{4}$ in. long and were at first of three widths: $\frac{1}{16}$ in., $\frac{1}{8}$ in. and $\frac{1}{4}$ in. The $\frac{1}{4}$ in. bar was presently discarded as providing nothing that was not observable in the $\frac{1}{8}$ in. bar. The bars were presented with their long dimension vertical.

The preliminary observations indicated that little was gained by using flash frequencies of other than 6 and 10 F.P.S. and later investigations agreed with this finding. Nor were the phenomena observed with all the phase settings previously noted sufficiently distinct to warrant their use.

Schedule of speeds and settings used in Part II:

1. Frequencies of 6 and 10 F.P.S.
2. Phase lead of ground over figure: 18° , 54° and 90° .
3. Phase lead of figure over ground: 18° and 54° .

The extensive series of investigations conducted on the effects of the width of the bar and reduction of boundary sharpness yielded data which in the present state of these investigations can be pre-

sented only qualitatively. The most unsatisfactory part of the experimental procedure on any work of this nature is the method of recording the observations. Not only are the phenomena themselves apt to become enormously complicated under certain conditions, but they are likewise so unstable and transitory as almost to defy characterization. Much was found to depend upon steady fixation and a vigorous attempt was made on the part of all three Ss to describe the effects only when fixation was thought to be rigid. Nevertheless, despite the difficulty in getting accurate descriptions of the effects, certain findings are clear.⁴

a. Zoning.—The area of the figure and the part of the field immediately adjacent to it was found to divide itself symmetrically into a series of zones or bands parallel to the two lateral boundaries of the bars (Fig. 1D). This zoning effect was easily visible to Subject C, who discovered the phenomenon with the elliptical figure. It was not readily seen by Subjects A and B under ordinary conditions and in the preliminary experiments had been missed altogether. Blurring the boundaries of the figure, however, increased markedly the visibility of the zones and the number of them. This effect applied to the bars viewed under red and green light as well as with white light. The zones seen with white illumination were more varied in hue and more numerous than those observed with colored light, although Subject C, whose perceptions were somewhat more complex, reported quite involved patterns of bands with the red and green illuminations in many instances.

Tables IV, V and VI show typical arrangements of color perceptions observed with the bar figures, using white, red and green illumination of both bar and field. The tables show the coloration of the control core of the bar and one half of the surrounding zones extending outward toward the field. The zone formation on the other half of the bar is merely the arrangement indicated in reverse order.

To check on the zoning process and to ascertain that the reduction of boundary sharpness was primarily instrumental in producing the borders two sets of control series were arranged, both without blurring. In one, maximal figure and ground brightness was used for all three illuminants with the vertical bars. In the other, intensity of illumination was reduced to that occasioned by the transmission loss (74 percent) when the ground glass disc was used. For Subjects A and B these conditions produced no notable zoning effects and were comparable in this respect to the results of the preliminary experiments on the elliptical figure. For Subject C the zones were present just as in the case of the previous unblurred conditions.

⁴ Thomsen (21) reports the same difficulties in analogous observations of intermittent light.

TABLE IV

COLORS OBSERVED WITH WHITE LIGHT AT VARIOUS FLASH FREQUENCIES AND
PHASE SETTINGS WITH BLURRED BAR FIGURES

Figure and ground brightness: 130 millilamberts *

1/8" bar. 6 F.P.S.																				
Region of Phenomena		Core			Zones												Field			
					1				2				3							4
Subject		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	
Phase lead	Gd. over Fig.	18	G	A		W	A			V								YG	Y	Y
		54	Y	Y	A	A	V		B	A								W	Y	Y
		90	Y	Y	GY		W	GY		V	V			B				A	Y	Y
	Fig. over Gd.	54	Y	Y	Y	Y	W	V		Y	V							YG	Y	Y
		18	Y	B	BG	R	W	V										W	Y	Y

1/8" bar. 10 F.P.S.																				
Region of Phenomena		Core			Zones												Field			
					1				2				3							4
Subject		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	
Phase lead	Gd. over Fig.	18	A	A	A		V											W	Y	Y
		54	YO	A	G	Y	R	V	A	Bl	P		B	A		V	B	GY	Y	Y
		90	OY	GY	YG		V	V			P			A			B	W	Y	Y
	Fig. over Gd.	54	OR	Y	OY	W	V	V			Y			A				YG	Y	Y
		18	BG	V	G		A											W	Y	Y

1/16" bar. 6 F.P.S.																				
Region of Phenomena		Core			Zones												Field			
					1				2				3							4
Subject		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	
Phase lead	Gd. over Fig.	18	Y	R	YG	Bl	A	A	A									Y	Y	Y
		54	Y	Y	GY	Bl	Bl	V	A	V	B							Y	Y	Y
		90	Y	Y	Y	Bl	Bl	V	A	V	A							Y	Y	Y
	Fig. over Gd.	54	Y	B	Y	A	Y	V	Bl	A	A	A						Y	Y	Y
		18	BV	B	G	Bl	W		A	A								Y	Y	Y

1/16" bar. 10 F.P.S.																				
Region of Phenomena		Core			Zones												Field			
					1				2				3							4
Subject		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	
Phase lead	Gd. over Fig.	18	A	G	GY		V											Y	Y	Y
		54	OR	O	Y	Bl	B	GY	A	V								Y	Y	Y
		90	R	Y	Y	Bl	V	GY	A		Bl							Y	Y	Y
	Fig. over Gd.	54	R	Y	GY	Bl	A	V	A		A							Y	Y	Y
		18	A	B	BG		W	B		V								Y	Y	Y

* Tables IV, V and VI present the colors observed in the zones on the right half of the bar. This region corresponds to the arrangement in Fig. 3. The zones appear on both sides of the figure, one half being a mirror image of the other.

TABLE V

COLORS OBSERVED WITH RED LIGHT AT VARIOUS FLASH FREQUENCIES AND
PHASE SETTINGS WITH BLURRED BAR FIGURES

Figure and ground brightness: .33 millilamberts

		1/8" bar. 6 F.P.S.																		
		Core			Zones													Field		
					1			2			3			4						
Region of Phenomena		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	
Subject		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	
Phase lead	Gd. over Fig.	18	R	P	G	R*	A	A									R	R	Y	
		54	P	P	G	R	A	Y		B	A		A	V		A	R	R	Y	
		90	P	P	G	R	B	Y			A		V			A	R	R	Y	
	Fig. over Gd.	54	P	B	Y		R	V		A	A						R	R	Y	
		18	R	R	G			A									R	R	Y	

		1/8" bar. 10 F.P.S.																		
		Core			Zones													Field		
					1			2			3			4						
Region of Phenomena		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	
Subject		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	
Phase lead	Gd. over Fig.	18	R	P	G		R		V								R	R	R	
		54	R	P	V	O	R	GY		R	Bl						R	R	W	
		90	P	B	O	OR	R	GY		R	O		V			A	R	R	W	
	Fig. over Gd.	54	R	P	Y	O	R	Y		A	B						R	R	Y	
		18	R	R	G	OY											R	R	Y	

		1/16" bar. 6 F.P.S.																		
		Core			Zones													Field		
					1			2			3			4						
Region of Phenomena		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	
Subject		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	
Phase lead	Gd. over Fig.	18	R	R	R												R	R	R	
		54	P	P	V		A		R								R	R	R	
		90	P	P	Br	R	R	A		A		B					R	R	R	
	Fig. over Gd.	54	R	P	GY		R	A									R	R	R	
		18	R	R	R												R	R	R	

		1/16" bar. 10 F.P.S.																		
		Core			Zones													Field		
					1			2			3			4						
Region of Phenomena		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	
Subject		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	
Phase lead	Gd. over Fig.	18	R	P	R												R	R	R	
		54	P	P	BV		A										R	R	R	
		90	P	P	BV		R										R	R	R	
	Fig. over Gd.	54	A	P	V	RO	R										R	R	R	
		18	R	R	R												R	R	R	

* In those instances in the table where a red boundary is shown adjacent to a field of the same hue, the zone is phenomenally brighter or darker than the field.

TABLE VI
COLORS OBSERVED WITH GREEN LIGHT AT VARIOUS FLASH FREQUENCIES AND
PHASE SETTINGS WITH BLURRED BAR FIGURES
Figure and ground brightness: 3.08 millilamberts

		1/8" bar. 6 F.P.S.																		
		Core			Zones													Field		
Region of Phenomena					1				2				3				4			
Subject		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	
Phase lead	Gd. over Fig.	18°	A	YG	A		A													GY
		54°	BG	G	G	A	Bl	GB			R									GY
		90°	BG	YG	G	W	Bl	Br												GY
	Fig. over Gd.	54°	BG	YG	G	W	Bl	R			A									GY
		18°	G	YG	GB		B	G			B									GY
																				GY

		1/8" bar. 10 F.P.S.																		
		Core			Zones													Field		
Region of Phenomena					1				2				3				4			
Subject		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	
Phase lead	Gd. over Fig.	18°	G	G			V													YG
		54°	G	G	B		YG	Br			V	G								YG
		90°	BG	YG	B	W	G	G			V	Br								YG
	Fig. over Gd.	54°	G	YG	G	G	A	W				R								YG
		18°	G	YG			A													YG
																				YG

		1/16" bar. 6 F.P.S.																		
		Core			Zones													Field		
Region of Phenomena					1				2				3				4			
Subject		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	
Phase lead	Gd. over Fig.	18°	G	G	A															G
		54°	B	G	GB	W		BG												YG
		90°	BG	G	G		Bl	R												G
	Fig. over Gd.	54°	BG	GY	G	W		R												G
		18°	G	YG	GB		A	G												G
																				GY

		1/6" bar. 10 F.P.S.																		
		Core			Zones													Field		
Region of Phenomena					1				2				3				4			
Subject		A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C	
Phase lead	Gd. over Fig.	18°	G	G	A															G
		54°	G	G	BG		YG	G			V									GY
		90°	BG	G	B	G	YG	Br			V									GY
	Fig. over Gd.	54°	G	O	G	G	YG	R			G									GY
		18°	G	R			YG				G									G
																				GY

b. *Effect of width of figure on number of zones perceived.*—The number of zones produced by reduction of boundary sharpness was roughly related to the width of the bars investigated. The wider (1/8 in.) bar produced more zones on the whole than the narrow (1/16 in.) bar. There was, however, a condition with white light

for Subject A in which the narrow bar produced more phenomenal borders. Under the rest of the conditions and with all Ss the wide figure produced slightly more numerous zones. A breakdown of Tables IV, V and VI is shown in Table VII. Here the number of

TABLE VII
ONE HALF NUMBER OF ZONES SEEN BY SUBJECTS A, B, C UNDER THE VARIOUS
CONDITIONS PRESENTED IN TABLES IV, V AND VI *

Width of Bar and F.P.S.	Subject	White light			Red light			Green light			Total
		A	B	C	A	B	C	A	B	C	
1/8" 6 F.P.S. 10 F.P.S.		5 3	9 8	6 11	3 4	7 6	12 10	3 2	5 7	7 6	57 57
	Total	8	17	17	7	13	22	5	12	13	114
1/16" 6 F.P.S. 10 F.P.S.		11 6	9 7	7 6	1 1	6 3	2 0	2 2	2 8	4 3	44 36
	Total	17	16	13	2	9	2	4	10	7	80

* The number of zones tabulated corresponds to the region indicated on the right side of Fig. 3. There are actually twice as many boundaries, since the zones are arranged symmetrically around the central core.

zones perceived for one side of the bar is presented according to the various conditions of the observations.

c. Instability of the subjective borders.—It has already been emphasized that the colored perceptions were most difficult to observe. Their fleeting, nebulous appearance is undoubtedly of the utmost theoretical importance. Of importance also is the observation that the various zones and their hues did not appear immediately for any of the observers, but took some seconds or even minutes to develop to what was judged to be their full form. During this developmental time they underwent much fluctuation and when at last they reached a more or less stable form ⁵ they were described by S.

d. Long term development of subjective chromatic perceptions in observers.—A factor related to the foregoing is the observation that the naive observer in these and similar stimulus situations (e.g., after-images, flight of colors) often sees little or nothing. With continued observation from day to day and week to week, however, the saliency and complexity of the perceptions grow.⁶ How long this process continues is unknown. Two of the observers in these studies have been working on subjective color phenomena for several years and still occasionally unearth effects which are new to them.

⁵ The term 'more or less stable form' is intentionally vague. It is doubtful if the subjective phenomena with which we are dealing here ever reach an entirely stable form. Observations of 10 to 15 min. duration disclosed continued slow fluctuations in the character of the borders.

⁶ Ives (14) encountered a similar effect when studying the 'flight of colors.'

e. Field phenomena.—Accompanying the borders surrounding the bars was an impressive and beautiful array of field effects. These long-known phenomena (19) producible by intermittent light were not extensively investigated here, but were studied briefly to see if they bore any relation to the borders observed on the bars. Special investigations of these field phenomena will be discussed in another paper. It will be sufficient here to summarize briefly the findings:

(1) The surrounding field usually took on a characteristic desaturated hue after a few minutes of observation. The field hue accompanying the borders is given in Tables IV, V and VI.

(2) A ubiquitous violet cloud was observed to float about the center of the field and to influence the coloration of the zones whenever it crossed the region of the figure. Edridge-Green (6) has suggested that this cloud may correspond to the macula, made visible, somehow, by the filtering action of the yellow pigment. However, since the cloud moves about, it cannot well be due to macular pigment, which remains fixed.

(3) There were observed also a variety of mobile geometrical patterns too numerous to mention. These filled the entire central portion of the field and were present most of the time. All these and the above-mentioned phenomena were evident under all conditions of illumination and intermittence.

(4) The field effects were present under a condition where there was no figure in the field; i.e., M_1 with a desilvered area was replaced with a plain mirror. They were observable also with no intermittence, although they were very faint.

DISCUSSION

Two theories have been proposed to explain the fact that colors may be produced by the presentation of intermittent achromatic stimuli. One holds that the various photochromatic retinal processes have different starting and stopping times and that consequently different chromatic resultants have different 'resonance' frequencies. The other asserts that the colors are due to modulations of the optic nerve impulse volleys which result from complex temporal patterns of retinal stimulation.

Inadequacy of the Temporal Lag Explanation.—The chief difficulties of the lag theory are to be found in two facts:

a. Colors are producible under various conditions of stimulation with monochromatic red illumination so chosen as to act upon the R retinal process only. These conditions include intermittent figure-ground patterns and intermittent and steady homogeneous fields.⁷

⁷ See also Abel (x) on the Luckiesh-Moss pattern.

b. The slow arousal of the zoning effect with blurring and the general instability reflected in the long term fluctuation of the zones.

Fry (11) attacks the temporal lag explanation of the mechanism of the Benham disc. If his demonstration is correct, the color is determined not by the position which the concentric arcs occupy relative to the leading edges of the black and white sectors, but rather by the particular temporal pattern of intermittence, determined by relative positions of all disc parts. If the internal relationships between the sectors and the rings are kept constant, shifting the rings with respect to the leading edges of the discs produces no different effects. Fry's finding is not clearly substantiated by the results presented here, although the reports obtained from Subjects A and B, on the figures observed with white light without blurring, indicate that shifting the phase relations produces little variation in the coloration of the figure. This is to the same degree true of the effects of changing the flash frequency (Tables I, II and III). Under these experimental conditions the phase relations were varied in accordance with Fry's procedure; i.e., any shift in phase was always made so that the absolute lengths of the light and dark phases remained the same.

If, however, the results of conditions under the blurring technique are considered, it is seen that shifting the phase produces rather wide, though not consistent, variations in both the color of the core and the attendant zones. Reduction of boundary sharpness introduces more variability in the subjective colors.

Inadequacy of the Modulation Explanation.—While Fry's analyses (11, 12) have made significant and valuable contributions toward showing that the mechanics of the end-organ processes are not adequate for an explanation of the colors perceived with the Benham disc, it is doubtful if the modulation hypothesis is sufficiently comprehensive to deal with the formation of multiple boundaries, the intermittent and steady field effects, the instability of the colors and zones and the long term developmental effects. Certainly these are not readily explained by a "complicated stimulus pattern which involves the stimulation of adjacent areas of the retina with different temporal patterns of intermittent white light" (12, p. 464).

The results of this study suggest that concepts of disparate latencies and of modulation of receptor and nerve discharge are inadequate, and that a theory of field articulation in terms of total and partial stimulus gradients is more promising. Such a theory may utilize the concepts of modulation and disparate latencies, but in forms so generalized that they apply not to single receptor cells or nerve fibers but to networks which may very well be structurally non-specific and capable of supporting a great variety of excitation patterns.

Temporal non-uniformity or intermittence of excitation appears as a *sine qua non* of the Fechner colors and allied transient phenomena. Intermittence of excitation may arise in two distinct ways: (a) because of intermittent or variable stimulation, and (b) because of variations in the functional efficiency of the receptors and the associated nerve network. These last comprise presumably random metabolic variations in the optic sector which affect the functional efficiency of the visual mechanism. Faint articulation of the visual field occurs when the stimulus field is spatially and temporally uniform. The instability of the color patterns of the physically homogeneous field is probably the most nearly direct evidence for this postulated random variation of the metabolic condition of the visual process. At the same time the fact that relatively simple patterns occur as frequently as they do points to a mechanism of field articulation which needs very little material upon which to operate, and which seems to obey a law of minimum complexity—the Gestalt Law of Prägnanz, or something analogous.

If the temporal uniformity is removed and intermittence of stimulation is added to such a spatially uniform field, the perceptions become enhanced and complicated. Variations of the excitation pattern due to random metabolic variations in the receptor cells and nerve fiber network are somehow magnified because of the intermittent stimulation and are superimposed upon the variable excitation pattern that is due directly to the stimulation intermittence. The resultant variable excitation pattern is comparable in degree to heterogeneity to the excitation patterns of ordinary seeing when the field of vision is physically not homogeneous. Hence there are visual phenomena, although they correspond to no physical reality.

In the case of the investigations where an intermittent figure is seen against an intermittent ground, the boundary is defined by a brightness difference. Since the figure and ground illuminations were physically equal, the figure was visible only when it was to some extent out of phase with the field. Momentarily, then, there is a physical boundary, i.e., a stimulus gradient rising from the dark region to the light region. This stimulus gradient is obliterated when both regions are equally illuminated. Then there is again a momentary physical boundary and a stimulus gradient, but now the stimulus gradient is reversed. Finally this gradient disappears and a new cycle begins. This holds true for all phase relationships except two: one where the figure and ground illuminations are in phase and the figure is invisible; the other where the figure and ground illuminations are in directly opposed phase and the stimulus gradients are periodically reversed without the intervening intervals of figure and ground equality. In this experimental situation, then, the boundary is de-

finer by stimulus gradients that are being continually varied. Now the crux of the matter is that figure-ground segregation takes time and that here not enough time is available to permit complete development of any one of five possibilities: (a) homogeneous field, no figure, (b) bright figure in a dark ground, (c) dark figure in a bright ground, (d) a dark ground showing through a hole in the center of a bright region and (e) the reverse of (d). In any case, the boundary is rendered highly equivocal. This does not mean, however, that it will be lost or even necessarily diminished. Apparently perceptual segregation is obtained in the form of phenomenal boundaries based on hue differences rather than exclusively on brightness differences.

The retinal stimulus gradients, moreover, will not be the same shape under all conditions. Their steepnesses will depend upon the way in which the stimulus light is distributed over certain regions of the retina. The blurring technique may be considered to have the effect of producing a diffuse image of the figure on the retina. Here the stimulus gradient will undoubtedly have a slope less steep than in the case of no blurring. Blurred and unblurred phenomenal contours correspond to stimulus gradients of different degrees of steepness.

The fact that the colors are enhanced by blurring then follows. Making the boundary more indefinite by flattening the stimulus gradient increases the equivocality and calls forth reserve expedients, hue differences, which make for increased figure-ground segregation. Since this effect seems to be independent of the composition of the light, it cannot depend solely on receptor processes.

Multiple boundaries with blurring, too, are thus related to the shapes of the stimulus gradients. Inasmuch as a blurred phenomenal contour corresponds to a flat gradient there would exist a wide zone of indefiniteness and a broad area in which the boundary-forming process could operate.

SUMMARY

1. A new and more versatile figure-ground technique was used to study certain visual transient phenomena (Fechner-Benham colors).
2. These color patterns may be obtained with intermittent or non-intermittent monochromatic red (no wave length shorter than $650\text{ m}\mu$), and green (spectral centroid $560\text{ m}\mu$) illumination as well as with white light.
3. Under conditions of intermittence reduction of the boundary sharpness of the figure produces a series of unstable chromatic zones (multiple boundaries) around the figure. These zones do not arise at once but take some time to develop.

4. Change of phase relationship between figure and ground illuminations and of intermittence frequency produces greater change in the color patterns with blurred contours than with unblurred contours.

5. Colors may appear in stationary, physically homogeneous, intermittently illuminated fields under each of the conditions of illumination employed.

6. Two theories are briefly considered and a tentative hypothesis discussed. According to the latter, visual transient phenomena are to be interpreted in terms of a general figure-ground segregation process modified by random metabolic variations in the optic sector.

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